Star-Disk Interaction in Young Stars
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Last gasp of V1647 Ori: a brief post-outburst warm, molecular wind

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Abstract. Followup infrared spectroscopy is reported for V1647 Ori, a young star whose recent eruption illuminated McNeil's Nebula. Lines of H I, H_2, and CO are compared to previous observations. We find that the accretion rate fell two orders of magnitude and the CO bandheads disappeared at the end of the outburst. We also report a striking metamorphosis of the fundamental CO spectrum from centrally peaked profiles to emission lines with superimposed blue-shifted absorption lines and back again one year later. This remarkable change in spectral appearance indicates that the system did not return to equilibrium immediately following the outburst. In this paper we propose a mechanism to explain the emergence of a transient post-outburst outflow.

Keywords. Accretion, accretion disks, stars: V1647 Ori, formation, mass loss, circumstellar matter.

1. Introduction

The EXor V1647 Ori recently underwent an outburst that lasted two years (Kóspál *et al.* 2005; Ojha *et al.* 2006; Acosta-Pulido *et al.* 2007). During this event, the source brightened by a factor of 50 in X-rays (Kastner *et al.* 2006), by a factor of 40 in the red (Briceño *et al.* 2004), by a factor of 15 in the near-infrared (Reipurth & Aspin 2004), and by roughly a factor of 15 at wavelengths from 3.6 μm to 70 μm (Muzerolle *et al.* 2005). The rise time for the outburst was roughly 80 days (see Acosta-Pulido *et al.* 2007 for a compilation of I-band photometry of this source). This was followed by a plateau phase lasting ~700 days during which time the source faded by one magnitude in the NIR. Beginning in November 2005, the star faded to its preoutburst brightness in ~70 days.

From the brightening of the source, Muzerolle *et al.* (2005) concluded that the bolometric luminosity increased by a factor of 15 (see also Andrews *et al.* 2004) and the stellar accretion rate increased from $\sim 10^{-7} M_\odot$ yr^{-1} to $\sim 10^{-5} M_\odot$ yr^{-1}. Similarly, Gibb *et al.* (2006) inferred a stellar accretion rate of $\sim 5 \times 10^{-6} M_\odot$ yr^{-1} from the luminosity of the Brγ emission one year later. This value is somewhat larger than the typical accretion rate of a young low mass star ($10^{-8} - 10^{-7} M_\odot$ yr^{-1}; Bouvier *et al.* 2007), yet lower than is expected for a star of the FUor type ($\sim 10^{-4} M_\odot$ yr^{-1}; Hartman & Kenyon 1996).

During the onset of the outburst of V1647 Ori, observations of atomic lines with P Cygni profiles indicated the presence of a wind (Briceño *et al.* 2004; Reipurth & Aspin

2004; Vacca *et al.* 2004; Walter *et al.* 2004; Ojha *et al.* 2006). The hot ($T \sim 10,000$ K) and fast (-400 km s^{-1}) wind produced during the early phase of this event was escaping at a rate of $\dot{M}_{\rm wind}$=4×10^{-8} M$_\odot$ yr^{-1} (Vacca *et al.* 2004). This mass loss rate is much lower than that of the typical FUor or EXor (Hartmann & Kenyon 1996) and is comparable to that of a classical T Tauri star (cTTS; Hartigan *et al.* 1995). Curiously, the ratio of the mass loss rate to the accretion rate is two orders of magnitude smaller than the typical ratio for cTTSs (Cabrit *et al.* this volume). The absorption component of the P Cygni profile for several lines disappeared within a few months following the peak of the outburst in early 2004 (Gibb *et al.* 2006). The Hα line, however, retained a P Cygni profile throughout the outburst, indicating that a weaker wind continued (Ojha *et al.* 2006; Fedele *et al.* 2007). There were two different absorption components seen in Hα: a highly variable one at a velocity of -400 km s^{-1} and a steady one at -150 km s^{-1}. There was no indication of a lower velocity wind during the outburst.

In contrast to the hydrogen and helium lines, the fundamental NIR ro-vibrational lines of CO observed on 2004 February 27 were broad and centrally peaked (Rettig *et al.* 2005). The temperature of the gas was 2500 K and thus consistent with the CO bandhead emission at 2.3 μm. The width of the emission lines was shown to result from the Keplerian orbital motion of the gas within the inner disk surrounding the central star, similar to the broad emission line profiles that are observed around cTTSs and Herbig Ae/Be stars (HAeBes; Najita *et al.* 2003; Blake & Boogert 2004; Rettig *et al.* 2006; Brittain *et al.* 2007a). Observations obtained on 2004 July 30 showed that the CO lines remained broad but the temperature of the gas fell to 1700 K (Gibb *et al.* 2006).

In this contribution we report followup observations of the NIR spectrum of V1647 Ori, which were acquired immediately following the end of the outburst and one year later. The fading of the source indicates that the accretion rate had dropped and thus we expected the CO emission lines to fade as well (Najita *et al.* 2003). We present a moderate resolution spectrum spanning 1.1–4.1 μm and high resolution spectra centered at 5 μm. We find that the accretion rate dropped two orders of magnitude and the CO emission lines cooled. We also find, however, that the fundamental ro-vibrational CO lines underwent a striking metamorphosis, changing from centrally peaked lines to lines with blue-shifted absorption features and back again. Such a stunning transformation has not been observed from other young stars with similar mass-loss rates. We conclude this article by proposing a mechanism to explain this unique phenomenon.

2. Observations & data reduction

V1647 Ori was observed with the SpeX instrument at the Infrared Telescope Facility on Mauna Kea, Hawaii, in 2006 January. The observations and data reductions were carried out on our behalf by Dr. Wm. Vacca, to whom we are extremely grateful. SpeX is a moderate-resolution ($\lambda/\delta\lambda \sim 1200 - 2500$), near-infrared (1–5 μm), cross-dispersed spectrometer (Rayner *et al.* 2003). The data were acquired using standard observing procedures (see, e.g., Gibb *et al.* 2006) and were reduced using the SpeXtool package (Cushing *et al.* 2004). The telluric correction and flux calibration were performed using standard techniques, as described by Vacca *et al.* (2003).

High resolution spectra of V1647 Ori were also acquired with NIRSPEC at the W. M. Keck Observatory on Mauna Kea in 2006 February and with the Phoenix instrument at the Gemini South telescope in 2006 December and 2007 February. The data analysis and line equivalent width in these spectra are presented in Brittain *et al.* (2007b).

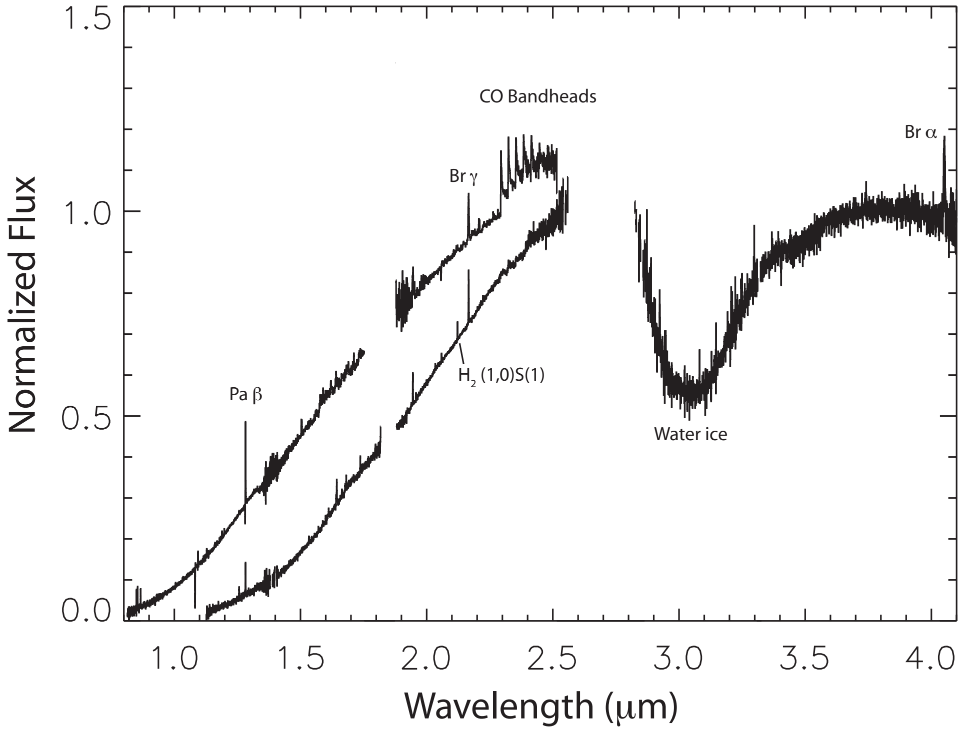

Figure 1. Comparison of the NIR spectrum of V1647 Ori during outburst and in quiescence. The spectra have been normalized to their their L-band fluxes. The spectrum that is brighter from 1–2.4 μm was observed in 2004 February, and the fainter spectrum was observed in 2006 January. The continuum faded ∼3 magnitudes during this time.

3. Results

3.1. *Atomic emission lines*

Examination of the moderate-resolution spectra taken during the outburst (2004 February) and following outburst (2006 January) reveals several changes (see Fig. 1). For example, Mg I, Fe I, and the CO bandheads disappeared, while H_2 and other unidentified emission lines emerged. Various features also changed shape. At the onset of the outburst, the Paschen series and two He I lines exhibited P Cygni line profiles (Vacca *et al.* 2004; Fig. 1), as did Hα (Briceño *et al.* 2004; Reipurth & Aspin 2004; Walter *et al.* 2004; Ojha *et al.* 2006). By 2004 November these lines had become centrally peaked (Gibb *et al.* 2006) and remain so now. A subsequent spectrum of V1647 Ori taken in 2006 November shows that the emission lines did not undergo significant changes post-outburst.

In contrast to the Balmer and Paschen lines, the Brackett lines revealed no evidence for a blue-shifted absorption component. Brγ has remained centrally peaked throughout the eruption, although its flux has dropped from $\sim 10^{-13}$ ergs s^{-1} cm^{-2} during outburst (2004 February; Gibb *et al.* 2006) to 1×10^{-14} ergs s^{-1} cm^{-2} post-outburst (2006 January). If one assumes that the Brγ line forms in the accretion flow and is minimally affected by a stellar wind, its luminosity can be used to infer the stellar accretion rate (Muzerolle *et al.* 1998). Based on the strength of the Brγ line, Gibb *et al.* (2006) determined an accretion rate of $\sim 5 \times 10^{-6} M_\odot$ yr^{-1}. Adopting the same stellar parameters as Gibb *et al.* (2006), we find a rate of $\sim 10^{-7} M_\odot$ yr^{-1} for 2006 January. Thus, in two years the accretion rate has fallen by two orders of magnitude from its peak value of $\sim 10^{-5} M_\odot$ yr^{-1}.

3.2. *CO spectrum*

Rettig *et al.* (2005) noted that the unblended CO emission lines observed during the outburst of V1647 Ori (e.g., the $v = 2$–1 P27 line at 2001.8 cm^{-1}) were symmetric and centrally peaked, and they concluded that the fundamental ro-vibrational CO emission originated in the inner disk. Fundamental CO emission lines are commonly observed around cTTSs and HAeBes (Najita *et al.* 2003; Blake & Boogert 2004; Rettig *et al.* 2006; Brittain *et al.* 2007a). The broadening of the emission lines, the absence of blue-shifted absorption, and the excitation temperature indicate that the emitting gas lies within a circumstellar disk (Najita *et al.* 2000).

V1647 Ori lies within the L1630 dark cloud, whose barycentric velocity is +26 km s^{-1} (Lada, Bally, & Stark 1991; Gibb 1999; Mitchell *et al.* 2001). Since the velocity of young embedded stars is typically within a few km s^{-1} of the surrounding envelope, we adopt this as the barycentric velocity of V1647 Ori itself. The CO emission lines, corrected for earth's motion, are found to be centered on the barycentric velocity of the star (Fig. 2). It is therefore unlikely that the emission lines are formed in an outflow.

Gibb *et al.* (2006) found that the shape of the CO fundamental ro-vibrational emission lines of V1647 Ori was unchanged from 2004 February to 2004 July, but noted that the gas had cooled modestly over that time span. We find that the CO emission spectrum has continued to cool. Indeed, the temperature of the emitting CO gas has fallen from 2400 K at the peak of the outburst to 1400 K in 2006 February. Additionally, the flux of the $v = 2$–0 bandhead has fallen from 3.6×10^{-13} ergs s^{-1} cm^{-2} to $\leqslant 1 \times 10^{-15}$ ergs s^{-1} cm^{-2}, i.e., a factor of $\gtrsim 300$. Such cooling of the gas is expected with a drop in the accretion rate (Najita *et al.* 2003; Glassgold *et al.* 2004).

The most striking change from the earlier observations is the emergence of a blue-shifted absorption feature in the 2006 February data (Fig. 2). The centroid of the absorption is shifted by −30 km s^{-1} relative to the velocity of the star. Its full width at half-maximum (FWHM) is 20 km s^{-1}. If this absorption is produced by gas that is in Keplerian motion around a $0.5 M_{\odot}$ star, and if it is observed against an extended continuum, then the gas must be located at a disk radius of $R = 1.1 \sin^2 i$ (AU). Interestingly, the observed blue-shift corresponds to the projected escape velocity from a $0.5 M_{\odot}$ star at a distance of $1.0 \sin^2 i$. Thus the spectrum is consistent with gas being lifted off the surface of the disk at $\sim 1.0 \sin^2 i$ AU from the star. A follow-up observation of the P30 line was acquired one year later with the Phoenix spectrograph on Gemini South. As is apparent in Fig. 2, the emission line is again clearly discernible, but there is no sign of the absorption component.

4. Discussion

Outflows from cTTSs and HAeBes are common, but fundamental ro-vibrational CO lines with blue-shifted absorption components are observed around none of the >300 such sources observed to date (Najita *et al.* 2000, 2003; Blake & Boogert 2004; Rettig *et al.* 2006; Brittain *et al.* 2007a; J. Brown private communication). This fact suggests that the appearance and subsequent disappearance of the warm, absorbing CO in the case of V1647 Ori is not due to the precession of a highly collimated outflow. Indeed the absence of blue-shifted CO absorption in the outflows commonly observed from other young stars indicates that their outflows do not contain warm ($\sim 10^3$ K) CO molecules.

Although the early outburst spectra of V1647 Ori showed no evidence of a 30 km s^{-1} outflow, one might hypothesize that the absorbing CO molecules formed in a decelerating wind that cooled as it expanded. As noted earlier, during the outburst, there were two

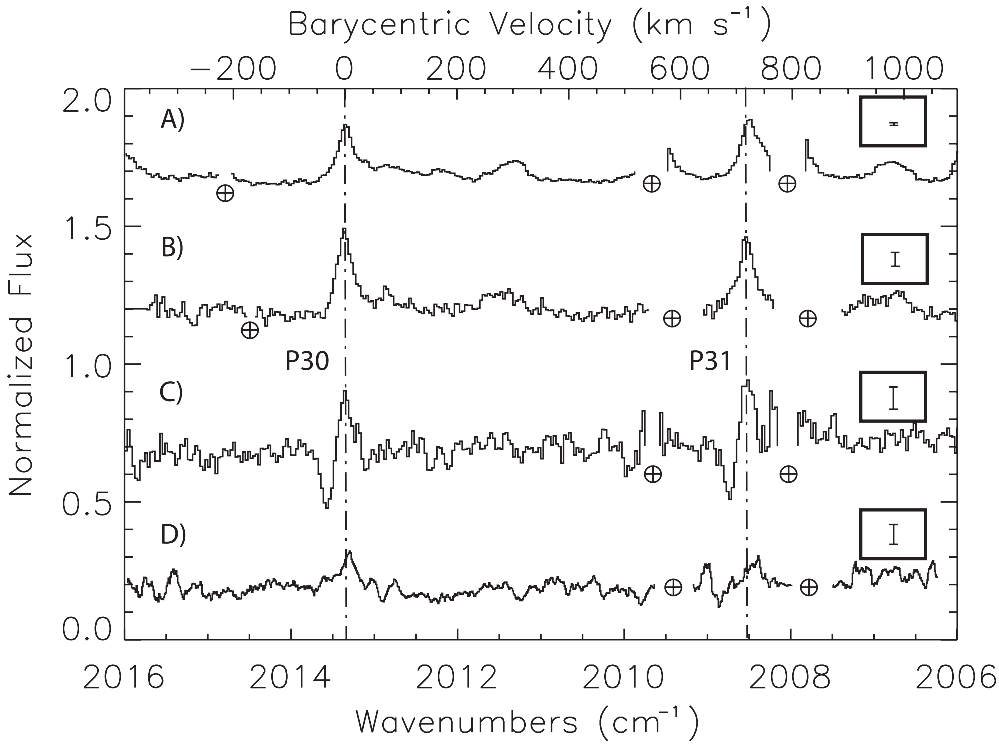

Figure 2. Detailed comparison of the high-J CO lines. The v = 1–0 P30 and P31 lines are plotted over four epochs spanning three years. An error bar has been plotted on the right side of each spectrum representing the standard deviation of the continuum. The spectra have been normalized, offset vertically, and shifted to the rest frame of the molecular cloud in which V1647 Ori is embedded. The spectrum acquired 2004 February is plotted in panel A (from Rettig *et al.* 2005). Six months into the outburst (2004 July) the CO emission lines remain broad and centrally peaked (Panel B; from Gibb *et al.* 2006). However, in 2006 February, after the star had returned to it pre-outburst magnitude, the CO lines have blue-shifted absorption features superimposed on them (Panel C). One year later (2006 December–2007 February) the CO lines return to their original profile (Panel D).

blue-shifted outflow components observed in Hα: a variable high-velocity component (∼400 km s^{-1}) and a steady component of moderate velocity (∼150 km s^{-1}; Fedele *et al.* 2007). If the lower-velocity gas decelerated at a constant rate to 30 km s^{-1} by 2004 July, then the wind would have expanded to 10AU. However, our observations on that date reveal no evidence of blue-shifted CO absorption (Fig. 2). By 2006 February, when the absorption first appeared, the wind would have expanded to nearly 40 AU. We think it is unlikely that the observed spectrum could be formed 40 AU from the star, and thus we conclude that the CO outflow observed in 2006 February must have emerged post-outburst.

We use a standard magnetospheric accretion model (Bouvier *et al.* 2007 and references therein) to account for the post-outburst outflow. Such models were first developed in the context of accretion onto neutron stars (Ghosh & Lamb 1979). Johns-Krull & Valenti (2000) have found that late-type pre-main-sequence stars typically have kG magnetic fields, which makes it plausible to suppose that the truncation radius of the disk is established by disk-magnetospheric interaction rather than by a disk-star boundary layer. In the standard magnetospheric accretion model, the truncation radius of the disk is

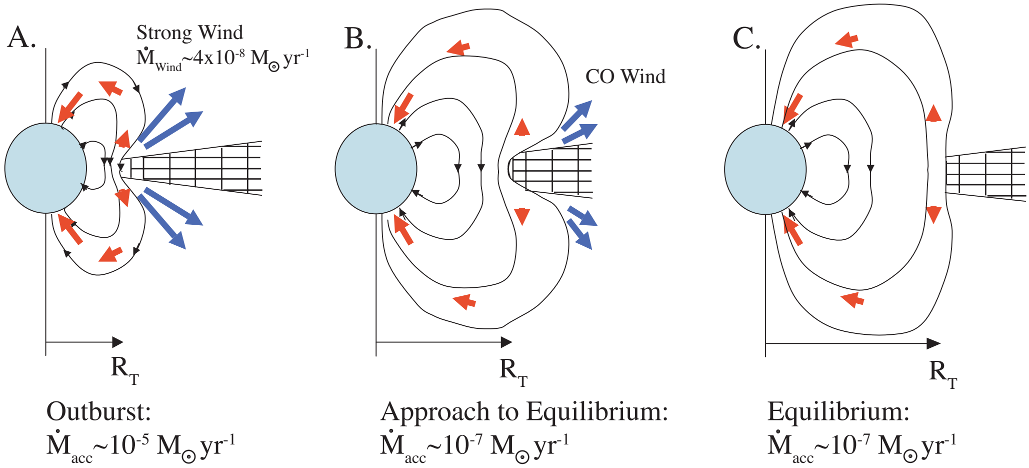

Figure 3. Schematic showing the disk-magnetospheric interaction in V1647 Ori in outburst and quiescence. The black arrows show the magnetospheric field, the blue arrows the outflow, and the red arrows the accretion stream in the magnetosphere. The outburst of V1647 Ori resulted from a sharp increase in the accretion rate of the star. The enhanced accretion pushed in the magnetic field so that R_T decreased and the magnetic field lines were pinched (A). This resulted in a fast, hot outflow. As the stellar accretion rate decreased and V1647 Ori approached quiescence, R_T increased (B). As the stellar magnetic field pushed back against the accretion disk, the field was once again pinched. This resulted in a slower, cooler CO outflow. Once the magnetic field returned to equilibrium with the accretion disk, the production of the warm outflow stopped (C).

related to the accretion rate by the following expression:

$$R_T = 7.1 B_{kG}^{4/7} \dot{M}_{-8}^{-2/7} M_{0.5}^{-1/7} R_2^{5/7}, \tag{4.1}$$

where R_T is the truncation radius in units of a stellar radius, B_{kG} is the magnetic field strength in units of 1 kG, $\dot{M}_{-8}$ is the stellar accretion rate in units of $10^{-8} M_\odot$ yr^{-1}, $M_{0.5}$ is the stellar mass in units of $0.5 M_\odot$, and R_2 is the stellar radius in units of $2R_\odot$ (Bouvier *et al.* 2007). This expression predicts that when the accretion rate decreases by two orders of magnitude, as in the case of V1647 Ori, the truncation radius of the disk should move outward by about a factor of three. Adopting the same parameters used to calculate the accretion rate, $R_{\rm star} = 3R_\odot$ and $M_{\rm star} = 0.5 M_\odot$, and $B_{\rm star} = 1$ kG, the truncation radius moved from 0.02 AU to 0.07 AU. If the movement of the truncation radius was contemporaneous with the optically observed fading of the source, then the stellar magnetic field pushed the inner edge of the disk back at a rate of ~1 km s^{-1}.

We use the following scenario to provide a qualitative explanation of the development of the CO outflow. When the accretion rate increased, the truncation radius moved inward, eventually reaching dynamical equilibrium with the magnetosphere (Fig. 3a). If the pinching of the magnetic field caused it to form an angle of $\leqslant 60°$ with the disk, then the magnetic field could drive an outflow (Blandford & Payne 1982). Evidence from simulations (Balsara 2004; Matsumoto *et al.* 1996) suggests that such disk-magnetosphere systems tend to form outflows when the system is undergoing the greatest amount of dynamical rearrangement. Consistent with simulations and disk wind theory (e.g. Ferreira *et al.* 2006), much of this warm outflow should emanate from the innermost radii of the disk. The accretion rate of V1647 Ori decreased by two orders of magnitude at the end of the outburst, and the truncation radius moved outward in response. During this

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readjustment, the disk and magnetosphere were not in dynamical equilibrium. As the magnetic field pushed the truncation radius of the disk back, the field once again entered a pinched configuration that resulted in a slower outflow at a larger radius (Fig. 3b). When the disk and the magnetosphere settled into dynamical equilibrium consistent with the reduced accretion rate, the angle between the magnetic field and the disk likely increased and the cooler CO outflow diminished (Fig. 3c). Thus the blue-shifted absorption is not observed in the post-outburst data (Fig. 2). This state is consistent with other cTTSs systems.

5. Conclusions

While accreting disks around low-mass stars are expected to interact with stellar magnetospheres and generate outflows (Hartmann 1998), the transformation of centrally peaked ro-vibrational CO emission lines to CO emission lines with blue-shifted absorption is unique. We suggest that the mechanism responsible for producing this outflow is distinct from the one that drives the outflow of the typical cTTSs. The rapid and dramatic change in the accretion rate that characterizes the EXor phenomenon provides an important opportunity to study the interplay between stellar accretion, the inner disk and outflows. This insight is key to reaching a satisfactory theoretical understanding of these events.

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